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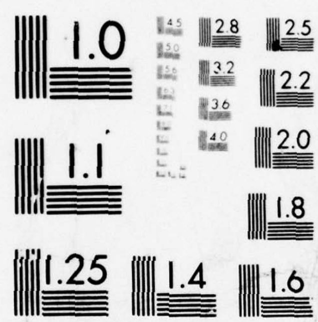

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DEFENSE SYSTEMS MANAGEMENT COLLEGE

PROGRAM MANAGEMENT COURSE INDIVIDUAL STUDY PROGRAM

GRAPHICAL EVALUATION AND REVIEW TECHNIQUE (GERT): A STOCHASTIC NETWORKING SCHEME FOR SYSTEMS ACQUISITION MANAGEMENT

STUDY PROJECT REPORT
PMC 77-1

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GRAPHICAL EVALUATION AND REVIEW TECHNIQUE (GERT): A STOCHASTIC NETWORKING SCHEME FOR SYSTEMS ACQUISITION MANAGEMENT

Individual Study Program

Study Project Report

Prepared as a Formal Report

Defense Systems Management College

Program Management Course

Class 77-1

by

Earle Howard Helgerson
Captain USA

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Study Project Advisor
LCDR Susan H. Anderson, USN

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DEFENSE SYSTEMS MANAGEMENT COLLEGE

STUDY TITLE: GRAPHICAL EVALUATION AND REVIEW TECHNIQUE (GERT): A STOCHASTIC NETWORKING SCHEME FOR SYSTEMS ACQUISITION MANAGEMENT

STUDY PROJECT GOALS:

To develop an appreciation for the existence of and need to address the realities of project uncertainty, risk and variability

To develop an understanding of the fundamental operating characteristics of GERT.

To develop an appreciation for the application potential that GERT offers the DOD Systems Acquisition Management Community.

STUDY REPORT ABSTRACT:

This study is designed to acquaint members of the Defense Systems Acquisition Management Community with the fundamental operating characteristics of a stochastic networking simulation scheme known as GERT (Graphical Evaluation Review Technique). The development of GERT has been structured around a conceptual framework supported principally by the PERT networking technique. Primarily geared to satisfying management needs, the evolution of GERT demands a minimum amount of technical expertise necessary to comprehend the fundamental concepts.

The principal theme of the study evolves about the ability of GERT to accommodate the realities associated with uncertainty, risk and variability which clearly separates it from the classical critical path networking models. Supporting this notion, the study discusses the stochastic realities that the DOD Program Manager must contend with on a daily basis.

The development of GERT fundamental logic properties is complimented by a discussion of its latest extensions. The thrust of the jesture is to afford the reader an appreciation of the flexibility and adaptability of the technique and to suggest GERT be a viable candidate for general DOD acceptance.

For those individuals desiring a more comprehensive appraisal of the GERT networking logic, an extensive bibliography has been prepared. Finally, the study offers a number of areas that foster both meaningful research efforts and potential benefits to the Defense Systems Acquisition Management Community.

SUBJECT DESCRIPTORS:

GERT	RISK ANALYSIS
SIMULATION MODEL	NETWORK FLOWS
NETWORK ANALYSIS	MANAGEMENT MODELS
GRAPHICAL EVALUATION AND REVIEW TECHNIQUE	

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Earle H. Helgerson, Cpt.USA	PMC 77-1	May 1977

EXECUTIVE SUMMARY

The primary intent of this document is to acquaint the reader with the fundamental operating characteristics of a relatively new stochastic networking simulation scheme referred to in the literature as Graphical Evaluation and Review Technique or simply GERT for short. GERT is a network-based simulation modeling technique which harbors great potential for anyone engaged in the tasks associated with planning, scheduling, controlling and analyzing complex projects existing in an environment of risk, uncertainty and variability.

While this study has been tailored to address the needs of the Defense Systems Acquisition Management Community, it offers a wealth of information to anyone interested in gaining an executive level understanding of the GERT networking model. The development of GERT fundamentals has been structured so as to demand a minimum level of technical expertise of the reader. A basic familiarity with the PERT networking scheme, while helpful, is not fundamental to digesting the material to follow. PERT is discussed only to the extent that it serves as an appropriate baseline from which GERT can be logically developed.

The development of GERT presented herein sacrifices much of the mechanics associated with "how" the technique executes its logic in favor of devoting more time to explaining the many facets of "what" it can do for management. Its principal strength draws from its ability to accommodate the realities

of risk, uncertainty and variability, and its tremendous capacity for adaptability. As a consequence, the study focuses upon the GERT logic properties designed to capture the stochastic elements surrounding project management.

Aside from being a rather versatile networking scheme, GERT exists in a continual state of refinement. To acquaint the reader with the potential horizon afforded in GERT, a number of its newest extensions are summarized. The discussion devoted to its extensions coupled with the development of core GERT fundamentals should furnish the reader with a rather comprehensive conception of its diverse applicability.

While GERT is presented as a technique that offers a wide range of options available to complement the management decision-making process, it is not to be construed to be a panecea for all management ailments. The study stresses the notion that if properly applied GERT has a great deal to offer the program manager. Judiciously employed, GERT can assist the DOD Program Manager in his efforts to guide his program through the maze of technical, political and financial "wickets" that are certain to materialize.

Finally, for those who are genuinely interested in gaining a deeper knowledge of the GERT networking properties, an extensive bibliography has been structured. Complimenting this, the study closes with a few areas that appear to offer meaningful research opportunities.

ACKNOWLEDGEMENTS

I would like to take this opportunity to extend grateful acknowledgement to those individuals whose thoughts, time and efforts made the preparation of the study a reality.

Special appreciation is tendered to my Study Project Advisor (SPA), LCDR Susan H. Anderson, USN, who supported my efforts from the state of conceptualization and continued thereafter to provide able advice and guidance.

To Dr. A. Alan B. Pritsker, distinguished Professor of Industrial Engineering at Purdue University and Dr. Gary E. Whitehouse, distinguished Professor of Industrial Engineering at Lehigh University, I extend a note of sincere gratitude for their efforts in guiding me to the most recent and relevant sources of information to support my study.

A special note of respect and admiration is extended to Dr. Pritsker who initially conceived the idea of GERT and to Dr. Whitehouse who materially aided in its development and expansion.

To my wife, Barbara, who graciously allowed the preparation of this report and my studies at DSMC take priority over anything else and proofread and typed the final draft of this report, I cannot acknowledge enough.

Finally, to my daughter, Shannon, who is too young to understand, I thank her for her moral support.

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SECTION I

INTRODUCTION

Perspective

The manner in which this paper is developed presupposes a number of assumptions relative to the reader that need to be brought to bear at the outset. To begin with, it is assumed that the reader possesses a basic familiarity with the nature and substance of networking schemes. Moreover, it is conjectured that the reader has an appreciation for the theoretical value or benefit to be gained from employing networking techniques as aids to the management effort. As a consequence, no attempt will be made to develop in minute detail the precepts of networking schemes. Classical networking techniques such as PERT (Performance Evaluation Review Technique) will be discussed only to the extent of establishing a logical point of departure and comparison.

Networking techniques from the point of view of this study are not considered to be paneceas for management ills. History is filled with cases wherein quantitative management models have been misapplied. To this end. networking schemes are valuable management aids under some conditions and totally inappropriate under others. Properly applied networking schemes can provide invaluable assistance to the management tasks associated with program planning, scheduling and control.

Finally, the theme of this paper is not geared to making one an expert in the application of network theory. Rather, it has been designed to provide an insight into or appreciation of a particular networking scheme in a very generalized manner. As much as possible the theoretical foundation and mathematical description of the technique have been deemphasized in favor of a more readily comprehendible format. For those who desire a more mathematically rigorous explanation of the technique, an extensive bibliography has been included in the study.

Purpose of the Study

The basic intent underlying this study is to expose the Systems Acquisition Management Community to a relatively new and very innovative networking scheme designed to facilitate project planning, scheduling and control under conditions of uncertainty, variability and risk. The specific networking technique presented is referred to in the formal sense as GERT (Graphical Evaluation Review Technique). This particular networking scheme will be discussed in contrast to the conventional networking techniques which, for the most part, are deterministic in nature. That is to say, these conventional schemes essentially contain no mechanism that can effectively capture the realities of uncertainty, nor can they readily relate to management the consequences of uncertainties in relation to cost, schedule, performance or resource allocation.

Specific Study Goals

In an effort to insure that the reader acquires an adequate degree of understanding or appreciation of GERT, a number of specific goals will be developed in the course of this study. These goals, largely by-products of the primary purpose, are as follows:

1. Development of an appreciation for the realities of project uncertainty, risk and variability (stochastic properties).

2. Development of an understanding of the need to address these stochastic properties and the possible consequences of failing to do so.

3. Development of an understanding and appreciation for the GERT networking scheme in terms of:

   a. What it is
   b. What are its capabilities/limitations
   c. How does it work
   d. What are its pros/cons
   e. Where can it be applied
   f. What are its variations

4. Development of the notion that if properly applied, networking schemes can assist the decision making process.

5. Development of the favorable impact GERT can have upon many Systems Acquisition Management problems.

6. Encouragement of wider application of GERT throughout the Defense Industry.

Value of the Study

The complexities of today's environment dictate that management must be able to effectively deal with uncertainty, risk and variability in order to survive. The fact that

survival is at stake suggests the potential values of management models that are designed to incorporate the realities of stochastic elements. There is little doubt that the Program Manager on a daily basis must commit some of his scarce resources to the task of coping with uncertainty. To this end the GERT networking scheme may afford the manager the opportunity to quantify risks and to assess their impact upon his project. Fundamental to this is an understanding of GERT to the extent that a logical and intelligent evaluation of its applicability can be made. To dismiss the potential benefits of the technique because of ignorance is criminal--to reject it on the basis of a sound understanding of its salient operating characteristics is management at its best.

As the study unfolds, it will become apparent that GERT in and of itself possesses immense potential for positive contribution to the System Acquisition business. As such, it is only logical that one engaged in such an activity should at a minimum be familiar with it. The technique appears to be expanding in its application and acceptability at an accelerated pace. Although it may never enjoy the same DOD stature that PERT achieved during the early 1960's, it is postulated that the day GERT (or a close approximation to it) will start to permeate the Systems Acquisition Community is not far away. This possibility coupled with the fact that Program Managers should have a basic understanding of management techniques that effectively reduce the impact

of uncertainty is what this study is all about.

Organization of the Study

In spite of an earlier declaration that the intricacies of networking would not be presented, the study will start out with some very basic notions underlying networking schemes. This particular discussion will be limited to a brief exposé on the evolution of networking techniques. In particular, the technique known as PERT will be discussed as it or a variation thereof has been the most widely used technique within DOD Systems Acquisition. PERT has an added dimension in that it offers an excellent baseline from which GERT can be discussed and developed.

Before proceeding into the development of GERT precepts, a brief discussion of risk, uncertainty and variability will be developed. This notion is essential inasmuch as GERT evolved in an effort to deal with these complexities. Recognizing also that GERT is not the only technique designed to incorporate stochastic elements into a networking scheme, several other models shall be briefly addressed.

The body of the study is designed to develop the fundamentals of GERT in a logical manner. As the development unfolds each successive phase will be supported by graphical representations and examples. The degree of complexity of each portrayal will be kept as simple as possible to support the point or feature being demonstrated. As a consequence, an element of realism surrounding the examples has been

sacrificed to a certain degree. It is hoped that a proper balance between realism and simplicity exists to maximize the learning process. For those who become disturbed with this simplicity, a number of "real-world" applications of GERT can be found in the literature offered in the bibliography.

Upon development of the fundamental features of GERT, the discussion will shift to a brief discussion of some of the different variations of GERT that exist today. Following this, the study will address the issue of the conditions under which GERT would be an appropriate management tool to be employed. Next, some time shall be devoted to the inherent limitations embodied in GERT and how they might be circumvented. Finally, the study will close with a summary and concluding remarks that are felt to be important.

SECTION II

BACKGROUND

Networking Overture

The application of network theory and techniques is by no means in a state of infancy. The network schemes that flourish today are in a sense a modern by-product of an evolutionary process that began many years ago with the likes of Frederick Taylor and Henry Gantt (1, 10)*. As projects have become increasingly complex in scope and require greater quantities of human and material resource expenditures, the demand for networking techniques has become more intense. In an effort to meet the rising demand, network theory and application have developed rapidly in the past ten years.

Networking models or techniques are in their most basic form nothing more than methods of graphically or visually displaying the relationships that exist between various activities of a particular project or task. Properly constructed, they offer the manager a convenient way of seeing his project, however complicated, in a simpler fashion. In addition, it serves as an excellent vehicle for inter/intra-organizational communication with respect to project management. Perhaps one of the most useful by-products of network

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*Numbers in parentheses correspond to the reference number and page number(s) as listed in the LITERATURE CITED.

theory stems from the fact that in order to properly structure a network, management is forced to define all key project activities and their interrelationships within the context of the project. This required exercise typically becomes an "eye-opener" as it surfaces key interrelationships difficult to conceptualize otherwise.

All networking schemes to varying degrees embrace the aforementioned aspects. What differentiates one from another is the extent to which they can incorporate project complexities in terms of inputs, internal processes and outputs. Existing network management tools offer a wide range of modeling capability. A key to remember, however, is one should not conclude that technique A is better than technique B on the basis of their degree of sophistication or complexity alone. Such evaluation should be made in context with the process to be modeled and the ultimate outputs desired.

Evolution of PERT

Perhaps the most famous and widely employed networking scheme has been the technique known to many as PERT (Performance Evaluation Review Technique). Developed under the auspices of the Department of Navy in connection with the POLARIS Missle Project in 1958, it was heralded as a major breakthrough in support of the management tasks of project planning, scheduling and control (9). Closely allied with PERT was another networking technique referred to as CPM

(Critical Path Method) which in essence was its conceptual twin (13). Since CPM is in a sense a subset of PERT, it shall not be discussed hereafter.

PERT evolved in response to the management difficulties associated with a rather large and complex project. Conceptually, however, its operating characteristics are quite simple to comprehend. In its basic form it demands that three steps be performed:

1. The project must be divided into a collection of separate and definable activities.

2. The sequence in which the activities are to be performed and attendant interrelationships must be defined.

3. The time and resources required for each activity must be identified.

Although the foregoing steps appear to be quite straightforward, their accomplishment may be quite a different story. Their resolution is the only difficult task associated with PERT networking as the technique itself is simplistically mechanical. Moreover, the management benefits to be accrued will only be as good as the degree to which those three steps are successfully achieved.

To refresh one's memory of what a PERT network looks like, a simple one consisting of four events (circles or nodes) and four activities (arrows) is depicted in Figure 1 on the following page.

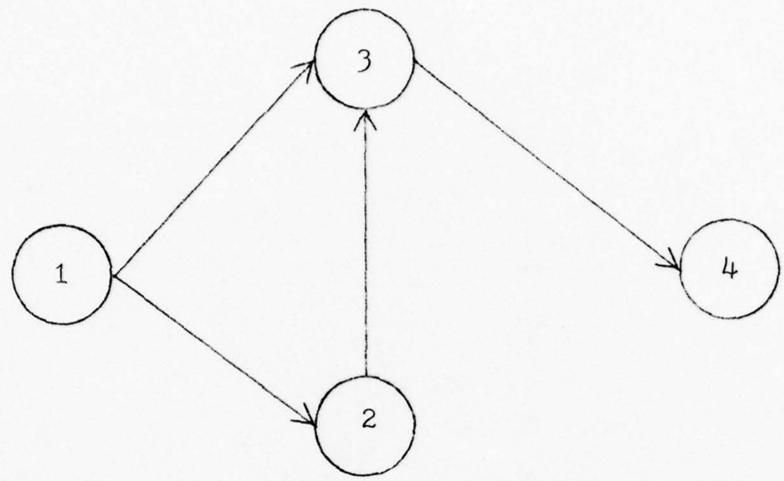

Figure 1
A Simple PERT Network

This network in a rather straightforward and simplistic manner illustrates a hypothetical project that begins with event 1 and ends with event 4. As structured, event 3 cannot be realized until both predecessor activities 1-3 and 2-3 incident to it have been completed. Similarly, activity 3-4 eminating from event 3 cannot begin or be released until event 3 has been realized.

PERT is a member of what is referred to as the probabilistic network family. As such, it recognizes and attempts to accommodate the variability or uncertainty associated witn activity time duration. Underlying the PERT time dimension is an assumption that all activity times can be adequately represented or approximated by a Beta distribution. This distribution in turn lends itself to a mathematical simplicity in that a mean activity duration can be

approximated by a combination of the shortest, most likely and longest times to complete a given activity.

Once all mean activity times have been computed and correlated with the network of activities, it is a simple task to determine the path(s) or series of interrelated activities that take the greatest amount of time to proceed from the beginning to the end of the network or project. This path is referred to as the Critical Path which is of primary interest to management. What differentiates the Critical Path from all the other network paths is that if any of its attendant activities require additional amounts of time the project completion date will slip in an equivalent manner. Providing visibility of the Critical Path to the manager affords him better control over the project destiny. If it appears that a critical activity is about to slip, the manager can marshal resources dedicated to subcritical activities to the problem area. If a critical activity happens to slip, the manager can then redistribute resources to critical downstream activities in an effort to get the project back on schedule.

To illustrate the notion of the Critical Path, the previous PERT network is replicated with the following activity duration times:

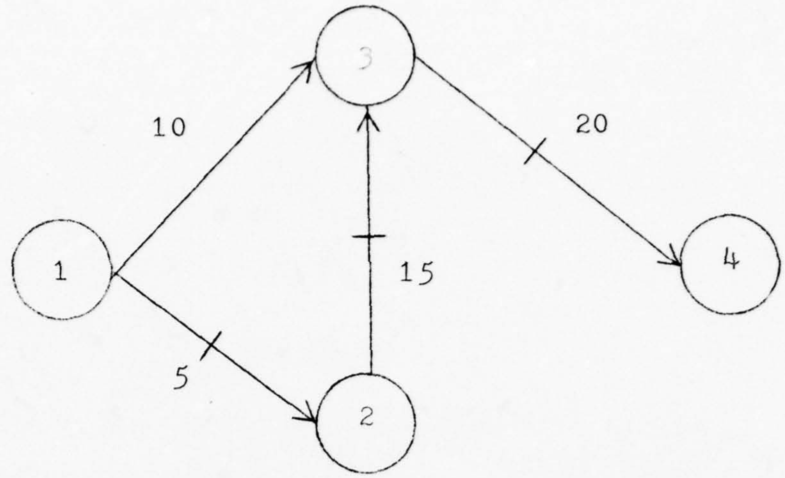

Figure 2
PERT Critical Path

The simplicity of this network allows one to see that only two paths exist to traverse the network, e.g. path 1-2-3-4 which requires 40 time units to fulfill, and path 1-3-4 which requires 30 time units. As a result, path 1-2-3-4 is the Critical Path. Similarly, subcritical activity 1-3 can take up to an additional 10 time units before it will have an adverse effect upon total project duration. Activity 1-3 is said to have 10 time units of slack.

Although exceedingly simplified, the foregoing demonstrates some of the management benefits embraced by PERT networks. First, it conveniently translates a series of activities and events into a very readible form. Secondly, it focuses management attention only upon those activities which drive the project duration time. In concert with the

Critical Path visibility, it suggests a starting point from which trade-offs or resource redistributions can be made in an effort to keep the project on or ahead of schedule. Finally, the Beta distribution assumption mentioned earlier allows the manager to define the probability of achieving any event in a given time or to calculate an interval estimate of the expected time to achieve a particular event. This final feature distinguishes PERT from the deterministic type network models and is the key to the task of dealing with project uncertainty.

Realities of Uncertainty

The elements of uncertainty and variability transcend virtually every aspect of our society. As a consequence, there is some degree of risk associated with anything one happens to embark upon. Fortunately, in many instances the risks and eventual consequences are so immaterial that one can safely ignore them. Unfortunately, DOD Program Managers are not able to enjoy this luxury with respect to their programs. Failure to account for the inevitable uncertainties quite often will spell certain disaster. The development and production of national defense weapon systems cannot afford to deteriorate at the hands of uncertainty. This, however, is a sad reality as it has been a rare DOD project that has not had a cost overrun, a schedule slip or a degradation in performance.

If one discounts poor management practices, it is postulated that the majority of DOD project ills have stemmed from the forces of uncertainty and variability. In program management within DOD there is an unending list of sources of uncertainty. Typically, the Program Manager is charged with tasks that have never been done before. This, coupled with other factors such as the unpredictable behavior of Congress, the diverse nature of the Program Manager's team and the complexities of the Systems Acquisition bureaucracy, generates a continuum of uncertainty and likewise risk.

Most experienced Program Managers recognize the existence of uncertainty and the relative consequences of not accounting for it. When one fails to account for uncertainty, an air of optimism is generated and eventually absorbed in program planning documents such as the Decision Coordination Paper and the Program Master Plan. When such optimism becomes an integral part of the program management philosophy, it is only a matter of time before project overruns start to surface, and in the long run the National Defense posture suffers.

Literature is filled with dissertations on how one might account for uncertainty within acceptable levels of risks. No single technique, however, exists with universal applicability. Any technique selected, whether it be objective or subjective in nature, must fit the scenario under study. Although there are no general purpose

solutions, it is safe to say that management must complement their subjective techniques for uncertainty accountability with the objectivity of analytical models. The difficult task is selecting the "right" analytical technique and establishing the proper relationship between its output and management judgment. Analytical techniques historically have been the recipients of varying degrees of skepticism. This skepticism typically stems from the fact that the analytical technique was either inappropriate for the occasion or its results were erroneously interpreted.

Generalized Network Techniques

Program Managers can cope with the problems of uncertainty only to the extent that selected management models can. Until recently program management did not have at its disposal network management models capable of accounting for the realities of uncertainty associated with its programs. The critical path techniques were for the most part deterministic with dependence upon singular or "best guess" time estimates. Beyond the Beta distribution assumption, PERT in a sense is deterministic in its networking logic.

Realistically, many if not all DOD projects will contain activities or paths of opportunity that may or may not materialize. Conventional networking schemes (to include PERT) assume in their logic that all activities must occur. Moreover, these techniques offer no mechanism to depict

multiple outcomes which is very unrealistic. All projects in their most basic form suggest at least two outcomes--success or failure! Finally, conventional network logic assumes that there is a singular critical path whereas reality suggests that all paths are to varying degrees subject to becoming critical.

In an effort to better approximate reality, a number of generalized networking schemes began to evolve in the early 1960's (4). Early schemes were developed in consideration of alternate paths and multiple outcomes in concert with decision trees. Since that time these techniques have become increasingly sophisticated. Probably the first technique to achieve a significant improvement in uncertainty accommodation was in the application of Monte Carlo simulation to the PERT logic (12). Superimposing simulation upon the basic PERT logic enabled one to replicate the inherent variability of activity times and gain insight into varying levels of path criticality. Today there are a number of techniques that have achieved a much greater degree of sophistication and realism. PROMAP, developed under the auspices of the Navy, added to PERT-Monte Carlo the capability of modeling activity probabilities as well as a number of additional features (5). Other techniques undoubtedly exist, but the most realistic and flexible networking scheme today is Graphical Evaluation Review Technique (GERT).

SECTION III

GRAPHICAL EVALUATION REVIEW TECHNIQUE (GERT)

PERT Limitations

A new management model such as GERT would be of marginal value if it did not represent an improvement over the models already in use. Moreover, its rate of acceptance and application is tied directly to the degree to which it out-performs its predecessors. While PERT continues to enjoy widespread application, it does have its limitations with respect to programs exhibiting complex interactions of uncertainty and variability. Basic PERT limitations which tend to make it a poor approximation of complex projects are (2):

1. All activities modeled by PERT must be completed before the project can be terminated.
2. All activities leading to a common event must be completed before that event can be realized and subsequent activities initiated.
3. No cycles or loops are allowed--that is once an event is realized it cannot be realized again.
4. The activity time durations can only be approximated by a Beta distribution.
5. The modeled project can only have a single outcome.
6. The Critical Path is always the path(s) with the longest expected elapsed time as represented by the mean activity times along that path.

In spite of these limitations PERT continues to retain its value and credibility in projects that do not invoke

these limits. This value or credibility, however, is conditioned on the premise that management is aware of PERT's inherent biasing effect. It has been shown that even when properly applied the PERT-generated time estimates are at best optimistic (1, 441-464). The degree of optimism which stems from the Beta assumption and manner in which the Critical Path is computed varies from one project to the next depending upon its structure. Unless management recognizes this built-in optimism and interprets the PERT outputs accordingly, project overruns will certainly become a reality.

GERT Overview

GERT is to a degree similar to PERT in that it represents projects in terms of a logical series of interconnected events and activities. However, it is much more powerful than PERT particularly in the sense that it does not share the PERT limitations as previously discussed.

Gert, or Graphical Evaluation Review Technique, evolved from a study of the terminal countdown of an Apollo space system in 1966. The particular problems being investigated at that time called for a networking scheme which could analyze networks containing probabilistic activities whose duration times were random variables. Networks exhibiting these two characteristics were subsequently described as "stochastic networks" (10, iii).

The original development of GERT was quite analytically complex, combining the disciplines of flowgraph theory, moment generating functions and PERT to resolve the complexities of stochastic networks (14, 243). Although the analytical foundation and applications are quite interesting in and of themselves, this study will not go into any detail relative to them. Unless one is reasonably skilled in flowgraph theory or moment generation functions, it is quite easy to become confused. Reference 14 contains a comprehensive discussion and development of the analytical implications of GERT for those so inclined.

In the course of developing the analytical foundation for GERT, it was discovered that a number of key system operating characteristics could not be replicated with existing analytic tools. As a result of the originators' intentions to make GERT as flexible and adaptable as possible, they shifted their efforts from the analytical approach to simulation. All the logical properties desired by GERT were translated into a family of computer simulation packages. The most common of these simulation packages is referred to as GERTS-IIIZ. Accordingly, the development of GERT fundamentals will evolve about the logic contained in that particular version.

GERT Fundamentals

Terminology

GERT insofar as the user is concerned is an activity-

oriented networking scheme. As such, activities are represented by arrows. Activities, which consume resources, are initiated and terminated by a set of unique and separate events. Events, which consume no resources, are represented by a family of logic nodes which are far more discriminating than those found in PERT.

When activities have been scheduled for eventual completion, they are considered to have been released by a particular event node. Similarly, an event node cannot release activities until it has been realized. Node or event realization can occur only after some combination of activities incident to or terminated at that node has been successfully released by a preceding node. Hence, the chronological sequence goes like this: predecessor activities having been released allow their terminating event node to be realized which in turn can release its successor activities.

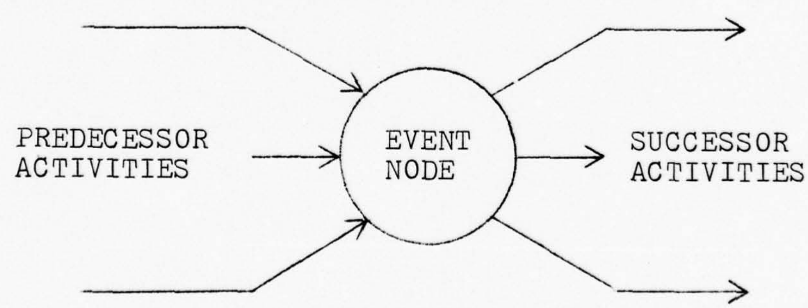

Figure 3
Activities versus Events

This particular sequence may be better conceptualized by referring to Figure 3. The event node is considered realized when a particular combination of predecessor activities have been released or scheduled for completion by a previous event node. In the context of this diagram the predecessor activities terminate at or are incident to the event node. Only after the event node is realized can the successor activities be scheduled for completion or released. This is nothing more than another way of viewing network precedence logic.

To facilitate a visual understanding of the logical properties associated with GERT, the developers have designed a unique symbology which the reader must be familiar with. This symbology deals exclusively in the manner in which the nodes or events are drawn. By modifying the configuration of the node, one can represent in a pictorial fashion the different node realization logic schemes and the activity scheduling logic. To do this, all basic GERT nodes have identifiable an input and an output side. The input configuration specifies the conditions under which that node (event) can be realized, and the output configuration denotes the manner in which the activities are released. This particular symbology scheme is depicted in Figure 4.

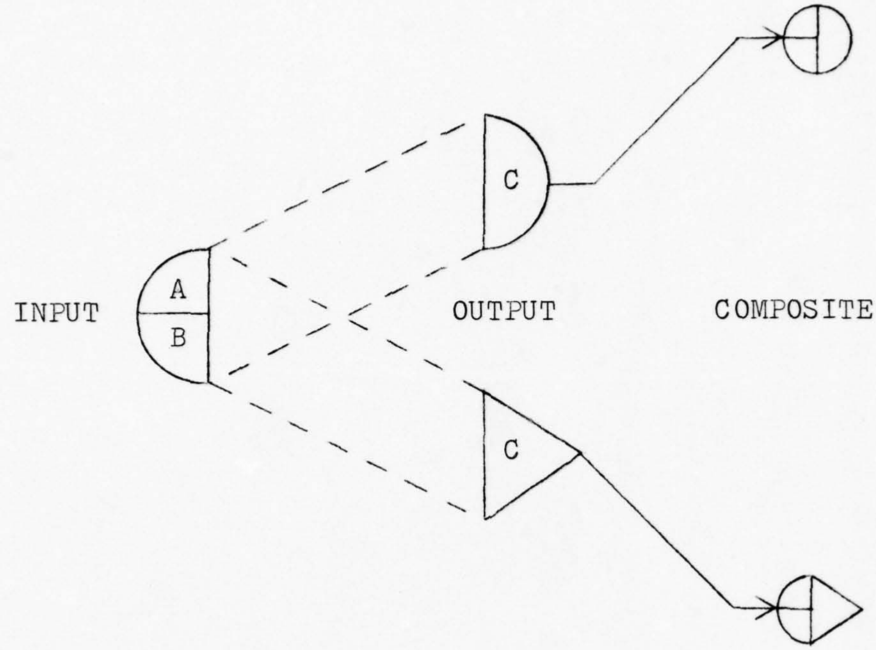

Figure 4
Node Symbolism

Probabilistic Branching

One principal advantage that GERT has over PERT lies in its ability to accommodate activities that have an associated probability of not occurring. The GERT logic that allows for the replication of this notion is known as probabilistic branching. Under conditions of probabilistic branching only one activity eminating from the corresponding event node will be released or scheduled for completion. Furthermore, the sum of the individual activity probabilities must be unity. In addition to this, GERT will also accept the standard PERT deterministic branching wherein all eminating

or successor activities have a certainty chance of occurring and all will be subsequently released.

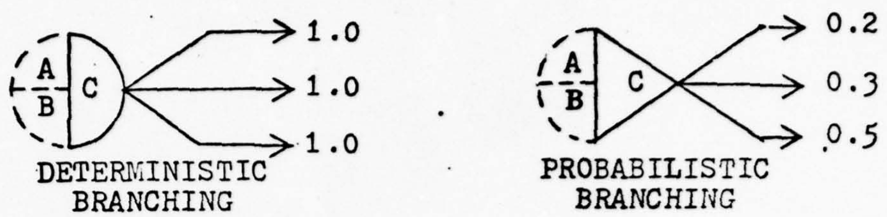

Figure 5
GERT Branching Logic (Output)

GERT branching logic is summarized in Figure 5. One will note that the type of activity branching defines the output configuration for the event node. For deterministic branching the output side of the event node is a semicircle, and for the probabilistic branching logic it evolves to a diamond. This is nothing more than a convenient method of communicating the branching concepts. Figure 6 depicts a network example of a phenomenon that may be all too familiar to the Program Manager which may solidify the concept of probabilistic branching.

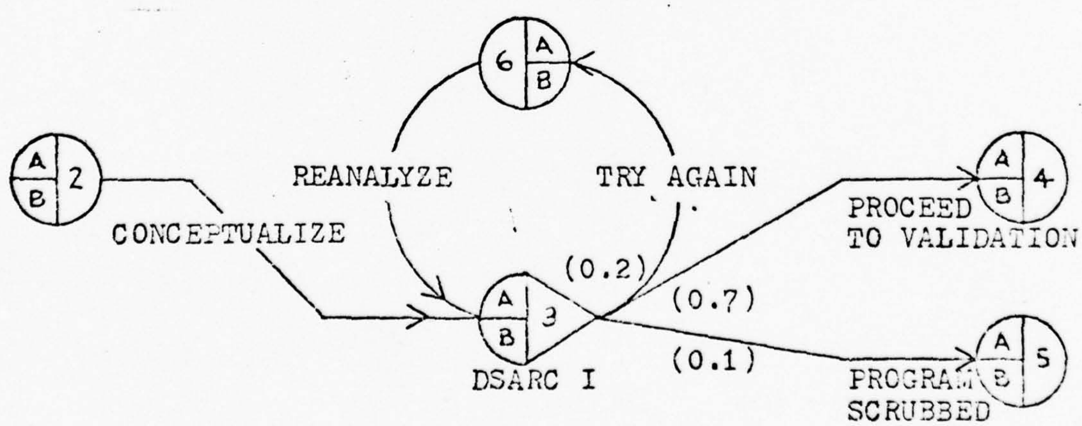

Figure 6
Example 1

Network Looping

In PERT after an event has been initially realized or an activity released, no mechanism allows either to occur again. Without this capability PERT cannot assimilate processes which contain reviews, reevaluations or reinspections which occur quite frequently in Program Management. GERT is believed to be the only technique that handles this sort of thing without going through a duplication of effort state. Figure 6 in a very simplistic manner illustrates this point. Anytime a Program Manager goes before a DSARC there exists that possibility that he will be sent back to the drawing boards which triggers the need for cyclical network logic. This sort of activity is easily ingested by the logic afforded by GERT and serves to make it an unusually attractive networking model.

Node Realization Logic

Perhaps one of the more difficult concepts in GERT to conceptualize is one of node realization logic. Node realization logic is nothing more than the conditions under which a particular node or event can be realized. GERT offers the user greater latitude and flexibility when specifying this sort of logic. From a symbology point of view, the specification of realization logic determines the input configuration of an event node and corresponds to the parameters A and B depicted in the foregoing figures.

In PERT only one type of node realization logic is permissible. That is, a PERT node or event cannot be realized until <u>all</u> activities incident to it (predecessor activities) have been released or completed. GERT is much more generous in that it allows the user to specify any one of four node realization schemes. Before discussing these logic schemes, one must understand what is embodied in the two parameters A and B.

Parameter A is the vehicle through which the user specifies the node realization logic for the <u>first</u> realization of a node. In cases where a feedback loop exists, a node may be realized more than once. Hence, the parameter B allows the user the ability to specify realization logic for <u>subsequent</u> node realizations. Furthermore, the logic for subsequent realizations may differ from the first. The initial discussion will focus upon the logic opportunities associated with parameter A and subsequently those with parameter B. The four logic schemes are as follows:

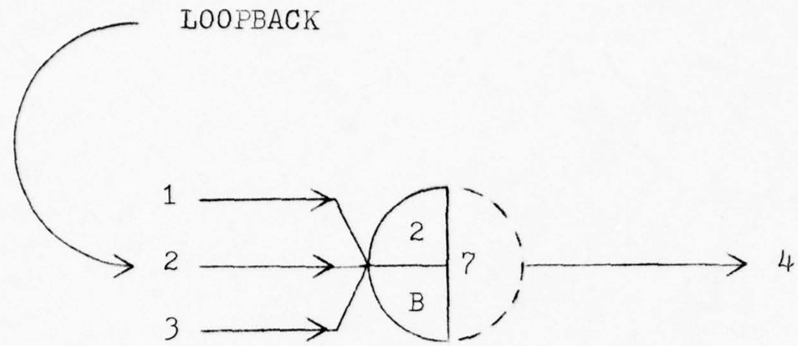

Figure 7
General Purpose Node (Input)

General Purpose Node: This is the basic node (input side) embraced in the GERT models. Referring to Figure 7, one sees event 7 which has three (3) activities incident to it. The significance of parameter A being set at 2 is that event node 7 will be realized (for the first time) only after it experiences two (2) activity releases within the group of predecessor activities. From a logic standpoint this can occur in several ways. The most obvious is that at the point when any two (2) of the three (3) activities are released the event is realized. However, if a loopback is permissible, event 7 can be realized when the same activity is released (repeated) a second time. In this particular example there is no requirement that all three (3) activities be released before the event is realized as PERT would have it. Once event 7 is realized, it can then release its successor activity, activity 4.

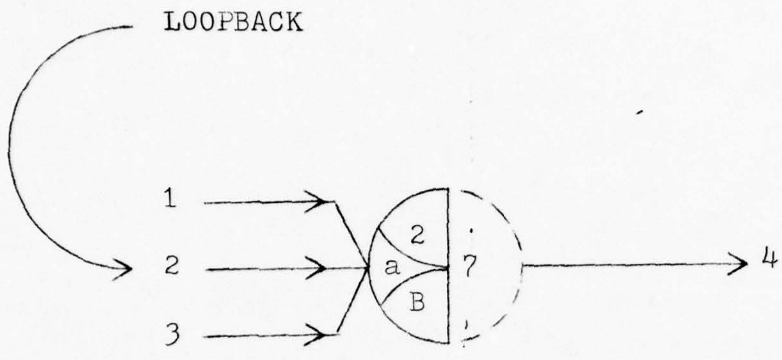

Figure 8
Type A Node (Input)

Type A Node: Figure 8 appears to be almost identical to that depicted in Figure 7. Event 7 again has three (3) activities incident to it. It differs from the general purpose node in that it will not allow node realization to occur until a combination of different activities are released. With parameter A as 2, event 7 will not be realized (for the first time) until two (2) different incident activities have been released. If parameter A was set equal to the number of activities incident to event 7, one would have the same logic embodied in PERT.

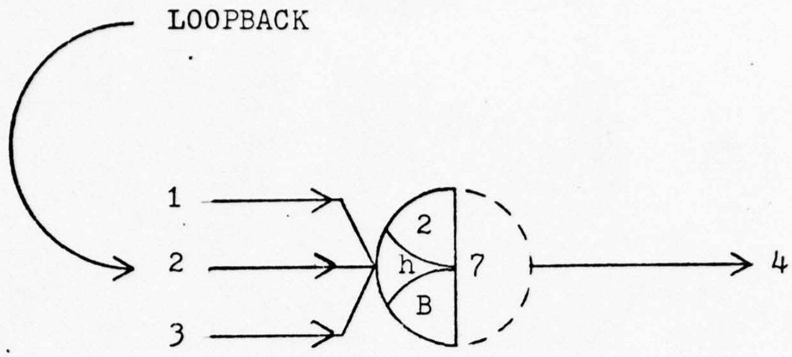

Figure 9
Type H Node (Input)

Type H Node: The third type of node, type H, as one might expect, accommodates even more complex logic. The H-node as depicted in Figure 9 is similar to the general purpose node in that it will allow event 7 to be realized when any combination of two incident activity releases occur. However, it differs in that upon realization it calls for the cancellation of any activities incident to that node that are in progress but not complete. Suppose for example, activities 1, 2 and 3 have all been released by preceding nodes and have scheduled completion times of 1 May, 1 June and 1 July, respectively. Then in this particular example, event 7 would be realized on 1 June. If an activity had been initiated or released prior to 1 June, its status would be "in progress but not complete" when event 7 was realized and, by the logic of the H-node, would be subsequently canceled. Activity 3 would only be initiated again if its start node was realized at some other point in time.

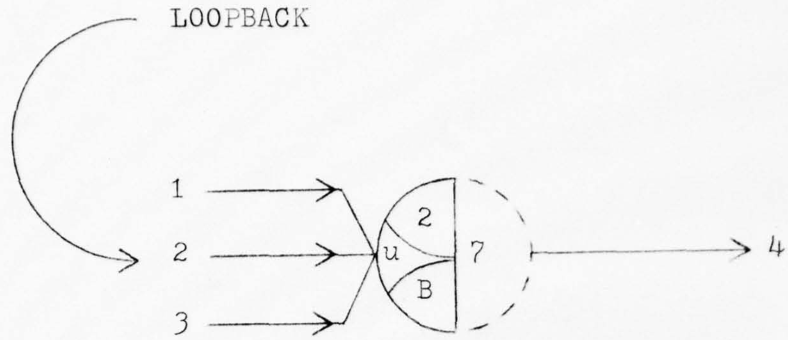

Figure 10
Type U Node (Input)

Type U Node: The final node, type U, combines the best of types A and H which allows more complex logic options. The U-node as in the case of the A-node requires different activity releases to occur before node realization. However, in conjunction with this requirement it triggers cancellation of any "in progress but not complete" activities incident thereto at the time of node realization.

At this point the reader should not become hopelessly discouraged at the complex decision logic embedded within GERT. The key concept is a fundamental understanding that GERT networks are quite capable of absorbing the complexities of the "real world". One will recognize the foregoing logic properties of GERT make it a much more adaptable technique than PERT. As a result, the Program Manager employing GERT can more realistically duplicate his problem and gain insight into the complex interdependencies as they

may exist.

The second parameter B allows the user to specify the conditions under which an event node can be realized on subsequent times. This sort of logic presupposes a loop-back condition exists relative to the node in question. Whatever value is selected for parameter B simply specifies the number of activity releases incident to the node that must precondition an eventual realization. The degree of difficulty associated with this parameter varies with the difficulty of the type of node one is dealing with.

Distribution of Activity Times

As one may recall, PERT network logic assumed that all activity times could be adequately approximated by a Beta distribution which in turn was fitted to three (3) time estimates. Unfortunately, this assumption is not valid for many real processes. GERT in recognition of this deficiency affords the user a wide variety of distribution options. This in turn adds to the versatility of the technique as well as enhances its capacity to accommodate many forms of uncertainty. Allowable time distributions afforded by GERT are as follows:

1. A Constant Value (CPM)
2. Normal Distribution
3. Uniform Distribution
4. Erlang Distribution
5. Lognormal Distribution

6. Poisson Distribution

7. Beta Distribution

8. Gamma Distribution

9. Beta fitted to 3 estimates (PERT)

10. Triangular Distribution

One might find it interesting to note that if GERT were employed to model a network with no loopbacks and all deterministic branching nodes utilizing the constant time domain, a CPM network solution would evolve. Similarly, if one specified the time domain as approximated via a Beta fitted to three (3) time estimates, the PERT network solution would evolve. In effect, both PERT and CPM are but logic subsets or special cases of GERT!

Multiple Source/Sink Nodes

The logic of PERT does not allow one to model networks that embrace multiple source (start) nodes and/or multiple sink (outcome) nodes. GERT, however, does recognize that many real processes call for multiple nodes. Not only can one specify multiple nodes but also specify how many sink nodes are to be realized before the entire network is realized or completed. Hence, it is possible to duplicate processes where more than one outcome must occur before the project can be terminated. This feature again adds to a growing capacity for adaptability found in GERT.

A Conceptual Example

Before proceeding, it may be useful to visually inspect

6. Poisson Distribution
7. Beta Distribution
8. Gamma Distribution
9. Beta fitted to 3 estimates (PERT)
10. Triangular Distribution

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A Conceptual Example

Before proceeding, it may be useful to visually inspect

an entire GERT networking diagram embracing a number of the foregoing features. Although the author did not develop the following network, it does illustrate the process that a Program Manager might be exposed to prior to getting his program ready for Milestone 0. For detailed development see (14, 411).

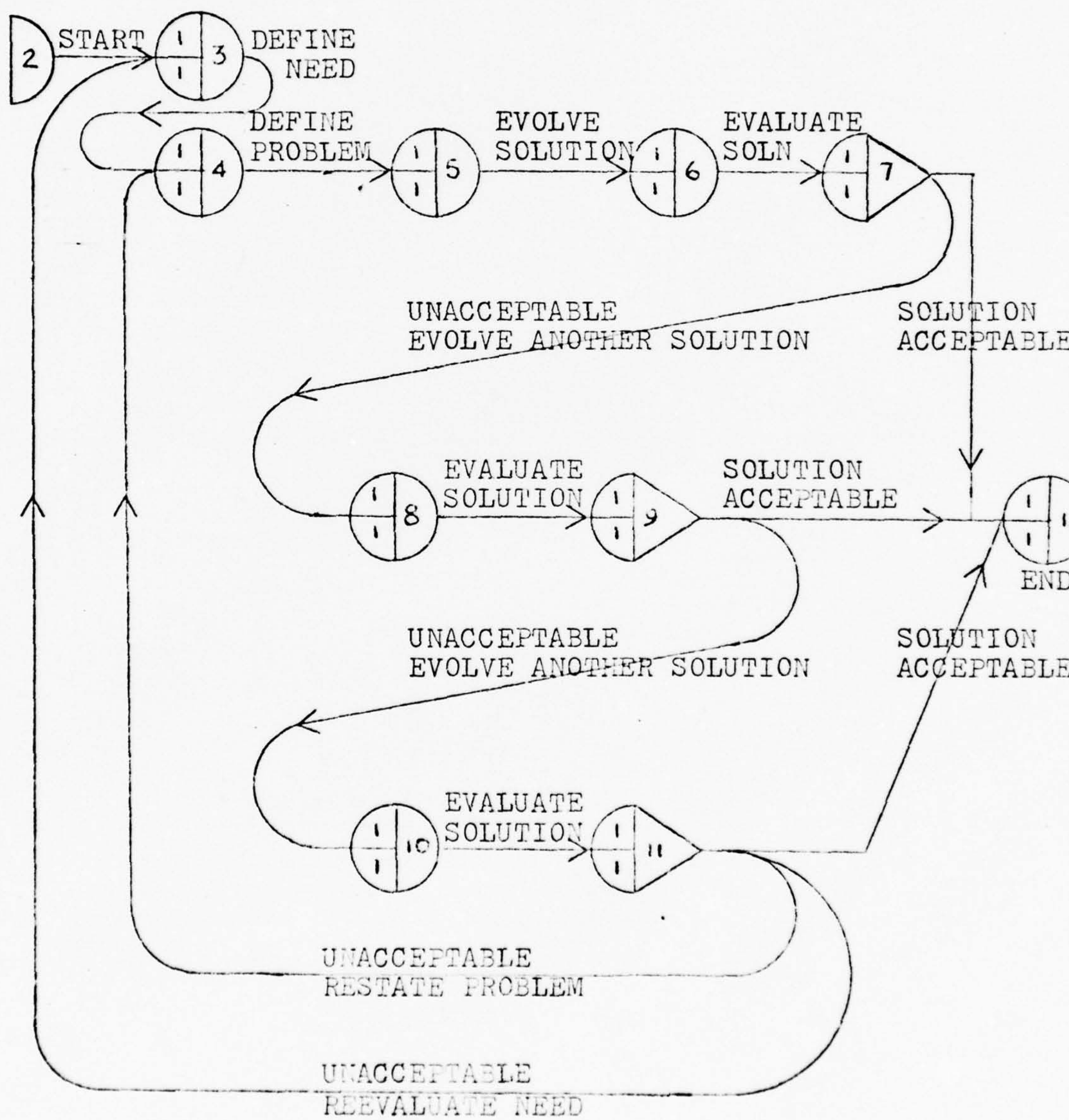

Figure 11
GERT Research Model

Although it is recognized that the foregoing example would be virtually impossible to support with accurate data, it does illustrate the communication properties displayed in GERT network representations.

GERT Cost Accommodation

An essential characteristic of any network model is in its ability to allow one to draw implications with respect to cost. GERT networks allow the user to specify on an activity basis a cost as it relates to the time consumed by the activity. Specifically, GERT will accept cost input which consists of two separate elements. The first element is referred to as the "fixed cost" portion which is totally unrelated to time. Secondly, the user can specify a "variable cost" portion which is time-dependent. Without modification, the GERT simulator will not accept any variable cost data that behaves in a nonlinear fashion with respect to time. Operationally, each time a particular activity is scheduled for completion or release the cost associated with the actual activity duration is computed and stored for later use.

Network Modification

GERT possesses an interesting feature which facilitates the evaluation of alternative management strategies without disrupting a simulation exercise. The user can, if desired, specify conditions under which network flow processing shifts

to an alternative series of events and activities which may or may not be representative of an alternate management strategy. Another useful aspect of this feature is it allows one to incorporate the by-products associated with learning curves. That is, with the passage of time activity times may become shorter and the probabilities associated with activity branching may be altered as the learning process evolves. Network modification takes place whenever user-specified activity occurs. This in turn shifts the logic to a predetermined location within the network. This feature is particularly attractive to those processes wherein learning curves are significant.

GERT Statistical Output

Unmodified GERT routinely generates a rather extensive collection of statistical reports designed to assist management. Data reports generated by GERT (IIIZ Version) fall basically into three categories: time statistics, cost statistics and probability statistics. Furthermore, these categories of statistics can be determined for not only the entire project or network but also for any intermediate EVENT.

Although probability statements and inferences can be drawn from the time and cost statistics, the category discussed above refers to both the relative frequency that a particular path or series of activities becomes critical and the relative frequency (criticality index) that a

given activity becomes critical. This sort of data should be of major concern to management. The levels of criticality allow the manager the ability to prioritize his management attention (management by exception) and provide a sound basis upon which decisions relative to resource allocations can be made.

With respect to time and cost statistical information, GERT allows the user to specify five separate types to be collected and reported. These types of data can be generated relative to:

1. The time consumed from proceeding from the source node (project initiation) to the first realization of a particular node or event as specified by the user.

2. The time consumed from proceeding from the source node to the last realization of a particular node as specified by the user.

3. The time consumed between successive realizations of a particular node as specified by the user.

4. The time consumed from proceeding between any two nodes or events as specified by the user.

5. The time delay that exists at a specific node between the earliest and latest incidental activity required for node realization.

Without getting into elaborate detail relative to each of the foregoing types, one may observe that GERT affords a rather detailed range of cost and time visibility. The actual degree of detail is left entirely up to the user. Time and cost data such as discussed can provide potential benefit to management tasks associated with time-cost trade-off

and benefit analysis, developing realistic budgets and budgetary controls, developing viable cost estimates relative to complex processes and so on.

As the network is simulated from start to finish many times, data relative to the operating characteristics start to form a "population sample". GERT, with respect to this population sample, automatically computes the sample mean standard deviation (estimate), the maximum and minimum values together with a corresponding histogram. The implications of all this are that one can make statistical inferences with respect to levels of confidence about schedules and expenditures. This in turn can complement management efforts to identify levels of risk that are acceptable. In addition, it allows management to construct control limits in accordance with their acceptable risk levels for monitoring actual cost and schedule.

If the particular network arrangement selected is a good approximation of reality and the inputed data is sound, the outputs generated by GERT provide invaluable planning capabilities. If management can live with the GERT-generated estimated performance characteristics, the task of tracking actuals with respect to planned becomes infinitely easier.

GERT Simulation

As was alluded to earlier, GERT network analysis is made available to management through a general purpose

simulation program known as GERTS-IIIZ. The entire package is coded in FORTRAN IV, drawing support from the FORTRAN-based simulation language GASP IIZ (11). As such, the simulation package is relatively easy to modify should management desire a capability that is not provided for in the original version.

GERTS-IIIZ performs network simulation by advancing time from one event to the next. While it has its own user-independent program logic, it essentially traverses the network from start to finish in accordance with user-specified logic. GERTS-IIIZ utilizes random number generators to replicate the probabilistic branching and activity time distribution logic specified by the user. Upon realization of all designated sink nodes, it cycles back to the beginning of the network to start a subsequent iteration. The user can specify how many times he wants the network to be simulated. On each successive iteration, statistics are collected in a manner in which the user has designated. Upon completion of the desired number of simulations, statistical summaries are printed out.

The actual simulation package and act of simulation is the easiest task in the entire process. The difficulty arises in the following areas:

1. Accurate translation of the key project operating characteristics into network logic.

2. Determination of required input data (time distributions, time-cost relationships and probabilistic branching characteristics).

3. Interpretation of the output.

4. Determination of the output versus judgment relationship.

Unfortunately, no easy answers or procedures exist for executing these responsibilities nor is there a simple decision rule for determining which area is more important. If the user thoroughly understands the process or feasible variation thereto under investigation, has ample historical data available or can accurately extrapolate it and is a logical and informed manager, chances are better management strategies will result.

GERT Extensions

The foregoing development of GERT fundamentals was done in relation to the GERTS-IIIZ simulation package although other versions exist. This development philosophy stemmed from the fact that GERTS-IIIZ is the most widely used package, is conceptually easier to understand and embodies the essential building blocks upon which GERT simulation rests. One must understand GERTS-IIIZ philosophy and logic before exploring other variations.

GERT network analysis has been expanding rapidly since its inception. Not only can it model dynamic processes, the technique itself has been in a constant state of dynamic evolution. As such, there is no guarantee that the contents of this report represent the latest state of GERT development. The fundamentals will remain basically intact with the future adding new features and refinement of older ones.

Q-GERTS

Perhaps one of the most rapidly expanding GERT variations is one in which allows the network analysis of complex queueing systems. This particular evolution centers around the introduction of a new node embracing storage capability amenable to queueing situations. Activities terminating at these Q-nodes represent demands for a particular service. The Q-node can be thought of as a service position. If the server is idle, the demand-for-service activity is scheduled for completion. If the server is found busy, the demand-for-service activity is mathematically placed in a queue or waiting line until the server can satisfy the demand.

The user of this particular version of GERT can specify thresholds at which a demand-for-service activity will "balk" away from the service position. This threshold is nothing more than the number of "customers" waiting in line for service. Furthermore, the user can specify service logic as either first-in-first-out (FIFO) or last-in-first-out (LIFO).

Q-GERT opens many options to the user. It provides an excellent vehicle for determining the optimum number of service positions required to satisfy a particular level of service. Cost versus level of service trade-offs can also be performed. Finally, one can, as a result of summary statistics, observe flow behavior through a particular system under study. Again, a very powerful tool is made available to management.

R-GERTS

Probably the most complex and dynamic version of GERT networking is the resource allocation model. GERT-IIIR allows the user to specify up to three different types of resources in addition to time that activities will compete for. In addition, the user specifies the activity utilization rates of these resources. With the introduction of constrained resources into the picture, the task of activity scheduling becomes quite involved. Since resource allocation decision logic tends to vary from one project to the next, it must be specified by the user as an input to the model. By its very nature the GERTS-IIIR becomes a test bed for evaluating various resource allocation strategies. Typical outputs from the resource model include such details as the degree to which various resources are utilized.

All Program Managers are infinitely aware of the difficulties arising from the issue of scarce resources. GERTS-IIIR offers a vehicle to assist in establishing more efficient use of existing resources as well as providing insight into how schedules and program costs behave with respect to various resource allocation schemes.

P-GERTS

Another version of GERT networking schemes is one that utilizes precedence or activity-on-node logic. This is nothing more than a different representation of interrelationships that exist between activities. As such, the

modeler is provided a wider degree of latitude in expressing lag and delay relationships that can exist between various activities. Some managers prefer this type of network expression as it more readily can address percentage of project completions and cost reporting (8, 123-124). All the capabilities discussed with respect to GERTS-IIIZ exist in the P-GERTS version.

Other Variations

As alluded to on several occasions, GERT networking models are quite flexible to the extent that the user can modify or tailor the existing logic to suit his needs. A survey of literature suggests at least three other GERT variations exist today although there probably are others:

1. SAINT: Developed by the Air Force for the analysis of man-machine systems (3, 216).
2. SMOOTH: Incorporates both continuous as well as discrete simulation concepts into the modeling and simulation analysis (3, 216).
3. GERTS-IIIQR: An amalgamation of GERTS-IIIQ and GERTS-IIIR which can be used to examine labor limited queueing systems (6).

GERT Applications

The inherent flexibility afforded by GERT networking models offers management an almost endless supply of opportunities for employment. If the management issue under evaluation can be reduced to a logical collection of interdependent events and activities, it is amenable to analysis via GERT. Because so many management issues faced by the

DOD Program Manager lend themselves to network analysis, it would be quite ridiculous to attempt to list them all. Available textbooks provide an enormous list of applications of PERT both actual and theoretical. As illustrated, GERT can do far more than PERT which suggests a level of applicability that may transcend reasonable human comprehension. By virtue of the various versions of GERT, any issue involving cost, schedule or resource allocation could probably benefit from GERT analysis.

The essence of GERT applications from the author's point of view evolves around the issue of risk assessment. Risk implies the existence of uncertainty, whether anticipated or not. Program Managers within DOD probably spend a significant portion of their resources and energies in an attempt to assess or quantify the risks of their program. If one is to be successful in reducing the adverse effects associated with risk, which invariably seem to be present, it is essential that the risks are quantified and analyzed. Moreover, defense policy demands that Program Managers identify and evaluate through <u>formal</u> <u>analysis</u> the risks associated with pursuing different management strategies. Risk assessment in this context is one of estimating the probability of success or failure associated with opting for various management strategies (7,11).

Risk assessment should be one of the principal drivers behind program development. It serves as a component element of the decision-making process that dictates which

course of action is to be executed. Through risk assessment, a Program Manager can identify high-risk areas within his program and subsequently develop strategy to reduce that risk.

GERT is nothing more than an analytical technique that can assist the Program Manager in his risk assessment task. Its capacity for handling probabilistic inputs representative of uncertain conditions allows the manager a vehicle wherein alternative management strategies can be tested artificially. In the final analysis, GERT network modeling serves as a useful technique to point the Program Manager in the direction affording acceptable levels of risk. Due to its flexibility, levels of risk can be manifested in terms of time, money and resources.

GERT, then, is appropriate as a management tool under conditions containing elements of uncertainty. Without uncertainty there is no risk and, as a consequence, no need for a management tool such as GERT. It is not necessary that uncertainties be explicitly defined. Given that the project can be modeled, one can experiment with and evaluate "what if" type questions--this of course is the power behind the GERT simulation aspects. Application of GERT network analysis ultimately can provide a positive contribution to DOD's effort to balance program risks and corresponding expenditures.

GERT Limitations

In spite of the many positive aspects of GERT, it is not perfect--it has its limitations. The ultimate degree of value of GERT analysis is predicated upon the user's ability to accurately conceptualize the process under study in terms of a network model and to translate that conceptualization into the GERT framework. This task demands that the user be experienced in or knowledgeable of every aspect of the process under investigation. The ease with which one can conceptualize and ultimately transform the operating characteristics of a project into the logic displayed by GERT can only be enhanced through "hands on" practice.

Closely aligned with the limitations associated with the transformation process is one of data estimating. It has been shown that GERT will handle a variety of probabilistic as well as deterministic data. The corresponding output will only be of value to the extent that accurate data descriptions were originally injected into the model. Thus, GERT is subject to all the limitations associated with data estimating techniques. That famous phenomenon referred to as GIGO...Garbage-In-Garbage-Out...is as much a part of GERT as it is with any modeling technique.

Finally, if one is interested in ascertaining optimum management strategies, GERT requires additional supportive analysis. The basic output summaries are descriptive or statistical in nature. They simply relate how the system

behaved under the conditions specified by the user. To identify the best or optimal way of doing business, one must process each possible strategy separately and then externally compare and contrast the results which may or may not lead to an optimal solution.

Although not necessarily a unique limitation to GERT network analysis, one must realize the costs associated with engaging this technique. Simulation exercises cost money both in the preparation of the input and in the computer time demanded to execute the program. Before electing to pursue a management problem with GERT analysis, one must weigh the associated cost of the analysis against the potential benefits to be accrued as a result of that effort.

SECTION IV

SUMMARY

Within the environment wherein the DOD Program Managers must operate, nothing is more certain than uncertainty itself. Anyone who might believe otherwise is probably a candidate for defeat at the outset. Managers, then, must first recognize this inevitability and then go about the task of developing strategy geared to deal with it. If one can quantify the degrees of uncertainty that exist, the business of generating appropriate contingencies is much simpler. The real difficulty stems from situations where uncertainties are not anticipated. It is not enough to wait until an uncertainty materializes, for at that time it may be too late. Evaluating the right "what if" issues is perhaps the most difficult task faced by Program Managers and certainly a most vitally necessary one.

The thrust of this entire study has been aimed at this terribly difficult task of dealing with uncertainty with which all DOD Program Managers must contend. In recognition that the issues of uncertainty typically cannot be solved solely on the basis of management intuition, judgment or experience, this study has discussed an available analytical management tool which embraces a vast degree of potential for the Program Management Community.

As developed throughout this study, the network modeling technique known as Graphical Evaluation Review Technique

(GERT) is a very flexible and revealing management tool. Its principal attraction stems from its ability to accommodate elements of uncertainty. Program Managers who typically get into trouble for things that they do not know (uncertainty) rather than those known should be made aware of models of such a nature.

This development of GERT was intended not to make the reader an expert but rather to gain an appreciation for what it is capable of doing. On the surface it may appear complex, but this is not true. Anyone with a PERT background can make the transition quite handily. The level of detail in the foregoing development has been designed to illustrate that GERT can model simple or complex processes existing both from a deterministic or stochastic point of view.

Properly applied, GERT can provide objective support to the decision making process which exists in a continuum of uncertainty. It provides an analytical test bed for evaluating and evolving management strategy. From a statistical view, it can translate complex operating characteristics into simple numerical summaries. Moreover, it allows the Program Manager the opportunity to identify acceptable levels of risk. In short, GERT embraces the potential for assisting management in any task relative to dealing with uncertainty.

SECTION V

CLOSING REMARKS

In closing, a word of caution must be brought to bear. There has been no intention, implied or otherwise, to suggest that hidden within the confines of GERT are all the solutions to management ills relative to uncertainty. As indicated earlier, the outputs provided by GERT are only as good as the inputs provided by the user. In addition, no matter how good the inputs seem to be the outputs must be tempered by the time honored judgment and intuition of management.

Like any modeling technique, GERT has been designed to assist or complement the decision making process. As a consequence, it should never be allowed to make the decisions--that is what management gets paid to do. Instead, a proper relationship must exist between the analytical output of GERT and management subjectivity--which is not a trivial task.

Finally, it is hoped that if GERT becomes a popular tool, it will not be applied in a haphazard manner. One must thoroughly understand that GERT cannot be applied to every management problem. Its applicability must be carefully analyzed before each and every execution. Failure to do so will inevitably generate management skepticism with respect to its value.

SECTION VI

AREAS OF ADDITIONAL RESEARCH

In the course of developing this study, several GERT-related topics embracing potential research benefit were surfaced. As such, they may lend themselves to interested students in future PMC classes.

Additional research relating to specific GERT application opportunities within DOD Systems Acquisition Management needs to be done. While GERT is capable of harnessing the realities of a surprising number of real world processes, some probably are more relevant to DOD than others. One approach which may or may not be feasible would entail identification of key Program Management problems common to all services and subsequently ranking them in relative order of importance. Having done this, one could then evaluate them in terms of their propensity to GERT analysis. This in turn would yield a greater insight into where the technique could or should be employed within DOD. This sort of project would be most appropriate for those with an extensive background in the Systems Acquisition business.

Another area that might be beneficial is one entailing a survey of the Program Management Community to determine what networking schemes are being utilized, why they are being utilized and whether or not they are indeed the most appropriate. This sort of project may be quite interesting and could suggest a revision in the PMC curriculum with

respect to current networking trends.

Cost estimating appears to be a profession that can use all the help it can get. Intrinsically, it seems that the manner in which GERT can generate not only time but cost estimates associated with different management strategies could assist one in arriving at a range of project costs that are realistic and obtainable. As a consequence, this area might be worthy of future research particularly for those with a cost estimating background.

For those students interested in the "ilities" associated with integrated logistics management, an interesting research study would involve developing a rationale or guiding philosophy for employing GERT network simulation to address the issues of maintainability, supportability, reliability and the like. On the surface, it appears that GERT offers some interesting prospects in the evaluation of maintenance concepts.

It was suggested earlier that GERT could accommodate the effects of learning curve theory in its network logic. Perhaps a study geared to exploring the notion deeper would be interesting and worthwhile.

Finally, for those interested in the topic of interactive computer graphics, it might be of interest to explore the implications of incorporating the GERT simulation logic into such a system. The prospects of making on-line network modifications and generating intermediate statistical reports in the course of simulation may prove to be of particular value to contingency generation and evaluation.

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